Final synopsis of Ph.D. thesis entitled

"Study of Scattering Behaviour of Lunar Surfaces Using Chandrayaan-2 Polarimetric SAR"

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1] Objectives

1. To study scattering behaviour of lunar surfaces like creator on lunar, ice, relogith is prime objective of proposed study.
2. To identify & detect &/or mapping of lunar resources is also objective of this proposed study.
3. To explore DFSAR data & process for polarimetry to get scattering composition of lunar surface is also an objective of proposed study.
4. To use different polarimetric decomposition techniques & co-relate the scattering mechanism to lunar surfaces is also an objective.

2. Statement of the Research Problem

1. It has restriction to study lunar features with in-situ observations, hence to explore lunar satellite data of microwave can be explored.
2. Longer wavelength microwave radiation can penetrate through cloud cover, haze, dust, and all but the heaviest rainfall as the longer wavelengths are not susceptible to atmospheric scattering which affects shorter optical wavelengths.
3. No precise research is available using microwave techniques to explore lunar surface.
4. Hence the proposed study consists of retrieval of scattering behaviour of lunar surfaces and interpret and detect the features of lunar on the basis of these mechanisms with the help of Chandrayaan-II polarimetric SAR data.

.3. Nature and Scope of the Work Done

A] Literature Review : Radar imaging and elemental mapping technologies have revolutionised lunar surface exploration. The basis for current SAR-based analysis was laid by early work conducted during the Apollo era, which revealed how different wavelengths interact with lunar regolith and offered fundamental insights into radar backscatter behaviour. These studies were essential in emphasising how surface roughness and dielectric characteristics influence radar responses. Studies employing compact polarimetric SAR data demonstrated that surface roughness and mineral distribution could be systematically associated with radar brightness. The deployment of the Chandrayaan-2 Dual-Frequency Synthetic Aperture Radar (DFSAR), which can perform full polarimetric imaging, marked a significant advancement. This dataset was used by researchers to describe the polarimetric behaviour of lunar features, and they found that the scattering mechanisms in crater interiors, rims, and ejecta blankets varied significantly. Numerous studies have effectively mapped rocky outcrops, ice-rich zones, and different types of terrain using decomposition models and microwave backscatter analysis tools. The DFSAR dataset has been used extensively to analyse the lunar surface scattering behaviour, especially within polar craters. Polarimetric decompositions, which showed clear surface and volume scattering patterns compatible with the presence of ice or high-porosity material, supported these conclusions. Radar-bright anomalies, which are frequently associated with ice-bearing soils or fine particulate matter, were identified thanks to improved clarity in radar returns from polar terrains. In parallel, recent research has focused on evaluating the agricultural potential of lunar regolith. Food sustainability is a major obstacle to lunar habitation, which calls for a careful assessment of in-situ soil resources. Plant growth simulation experiments in lunar soil analogues have yielded inconsistent results, with nutrient availability playing a major role in success. Researchers have evaluated the presence of important macro- and micronutrients necessary for plant development using elemental abundance maps produced by the Chandrayaan-2 CLASS instrument. Many lunar regions were found to have sufficient levels of iron and magnesium, which support the formation of chlorophyll and basic plant metabolism. However, serious deficiencies in nitrogen, phosphorus,

and potassium—elements essential to root development, energy transfer, and plant structure—were found. These results highlight the necessity of developing engineered growth substrates or targeted nutrient augmentation for possible lunar agriculture. Additionally, missions like Chandrayaan-3 continue to use elemental studies and polarimetric SAR for characterising lunar sites. Integrated SAR, optical, and spectroscopic datasets have been useful in identifying resource-rich regions, stable landing zones, and structurally coherent surfaces. The use of radar backscatter as a diagnostic tool has been further validated by modelling radar scattering from icy regolith, which has theoretically supported empirical observations. Combined, the research shows an increasing interdisciplinary convergence of planetary science, remote sensing, geophysics, and agricultural sustainability. This thorough basis underpins the current doctoral study, which attempts to combine elemental mapping and polarimetric SAR analysis to evaluate the lunar surface's physical and agricultural viability, especially in polar and cratered regions.

B] Present Work: Using cutting-edge radar remote sensing and elemental mapping techniques, the current doctoral research aims to conduct a thorough evaluation of the lunar surface's physical and agricultural potential. Using high-resolution data from the Chandrayaan-2 mission, specifically the Dual Frequency Synthetic Aperture Radar (DFSAR) and the Large Area Soft X-ray Spectrometer (CLASS), this study combines polarimetric SAR analysis with elemental evaluation based on X-ray fluorescence for interdisciplinary lunar surface studies. The first stage of this work involved characterising the fundamental polarimetric signatures of the lunar surface by processing full-polarimetric DFSAR data using MIDAS (Microwave Data Analysis Software). Pauli RGB visualisations, polarisation signatures, and scattering matrices (C3, T3) were generated and interpreted as part of the study. It made it possible to comprehend the dielectric responses and radar backscatter behaviour of different lunar terrains in greater detail, which paved the way for the identification of scattering mechanisms and polarimetric classification. Using sophisticated polarimetric decomposition methods like the Freeman–Durden, Cloude–Pottier, and Yamaguchi methods, the second phase of the study concentrated on the intricate scattering behaviour of lunar crater features. This allowed for the mapping and analysis of changes in surface, double-bounce, and volume scattering components in relation to particular geomorphic units, including shadowed zones, ejecta, and crater floors. This analysis demonstrated how polarimetric SAR can be used to locate radar-bright targets that indicate ice or high-porosity materials in polar regions, distinguish between different regolith maturity, and detect roughness anomalies. The work's third and last stage expanded the use of lunar data to evaluate the viability of agricultural endeavours beyond Earth. The presence of important macro- and micronutrients, including magnesium (Mg), calcium (Ca), sodium (Na), iron (Fe), aluminium (Al), and silicon (Si), on the lunar surface was assessed using elemental abundance maps obtained from CLASS during solar flare events. These were contrasted with the Food and Agriculture Organization's (FAO) list of terrestrial nutrient requirements. Promising magnesium and iron concentrations were found in the study, but there were significant deficiencies in nitrogen (N), phosphorus (P), and potassium (K), suggesting that nutrient supplementation would be necessary to support plant growth in a lunar environment. Collectively, these investigations offer a unique combination of geochemical analysis and SAR polarimetry for characterising the lunar surface. In addition to supporting more general goals pertaining to in-situ resource utilisation (ISRU), future mission site selection, and the long-term viability of human presence on the Moon, the work makes a substantial contribution to the scientific understanding of lunar surface properties. A new direction in remote sensing-based lunar studies is marked by the interdisciplinary approach used in this study, which tackles issues related to both applied lunar engineering and planetary science.

4. Research Methodology

The research methodology adopted for this doctoral work integrates advanced radar remote sensing techniques, polarimetric decomposition models, and geochemical analysis of lunar surface data acquired through the Chandrayaan-2 mission. The study was executed in three major phases, each involving specific data sources, processing workflows, and analytical methods, as outlined below:

4.1 Data Sources: Full-polarization and compact-polarization L-band data from Chandrayaan-2 DFSAR were acquired, covering various lunar regions, especially polar and cratered terrains. X-ray fluorescence data obtained from the CLASS (Chandrayaan-2 Large Area Soft X-ray Spectrometer) instrument were used for geochemical analysis, primarily focusing on essential nutrient elements. Global agricultural nutrient standards from the Food and Agriculture Organization (FAO) were referenced for comparison with lunar elemental distributions.

4.2 SAR Data Pre-processing and Polarimetric Analysis: SAR data were pre-processed using ISRO's MIDAS (Microwave Data Analysis Software) and supplemented by external tools for radiometric calibration, speckle filtering, and geometric correction. Stokes vector, coherency matrix (T3), and covariance matrix (C3) were generated for each scene to facilitate polarimetric feature extraction. Pauli RGB and eigenvalue-based decompositions were applied to generate polarimetric images and identify scattering behaviors associated with surface roughness, volume scattering, and double-bounce effects.

4.3 Polarimetric Decomposition and Scattering Mechanism Analysis: Freeman–Durden, Cloude–Pottier, and Yamaguchi decomposition techniques were implemented to separate different scattering components over diverse lunar geomorphic features. Entropy–Alpha–Anisotropy (H-α-A) analysis was conducted to classify scattering zones and assess regolith heterogeneity. The radar backscatter characteristics were correlated with known geological units such as crater interiors, ejecta blankets, and permanently shadowed regions (PSRs).

4.4 Elemental Mapping and Agricultural Feasibility Analysis: CLASS-derived XRF data were processed to produce elemental abundance maps for Mg, Ca, Fe, Na, Al, and Si across the lunar surface. These were spatially analyzed using GIS tools to assess regional variation and correlated with DFSAR-derived physical features. The elemental concentrations were quantitatively compared with FAO macro- and micronutrient benchmarks for terrestrial crops to evaluate the agricultural potential of lunar regolith. Deficiency mapping was performed to identify nutrient gaps, and suitability zones were proposed based on element synergy and relative availability.

4.5 Validation and Interpretation : The results from polarimetric decomposition were validated against reported dielectric models and previous lunar dielectric studies. Agricultural feasibility interpretations were aligned with published plant growth experiments on lunar simulants and matched with FAO thresholds. Integration of SAR-based physical parameters with geochemical data provided a multi-dimensional assessment of lunar surface suitability for human exploration and ISRU (In-situ Resource Utilization).

This multi-phased methodology enables a comprehensive, interdisciplinary exploration of lunar surface characteristics, combining microwave scattering behavior with elemental availability to support lunar colonization prospects. The approach ensures scientific rigor while addressing practical constraints for extraterrestrial sustainability.

5. Contribution Made to the Existing Knowledge

This doctoral research has made significant contributions to the evolving field of lunar surface analysis through the integrated application of polarimetric SAR techniques. The unique combination of Chandrayaan-2 DFSAR and CLASS datasets, interpreted in the context of planetary surface science and extraterrestrial agriculture, offers the following original and meaningful advancements:

1. First-ever comprehensive polarimetric characterization of the lunar surface using full-polarization DFSAR data processed via MIDAS, establishing baseline scattering behavior across diverse terrains, including crater interiors, ejecta regions, and permanently shadowed zones.

2. Novel application of advanced polarimetric decomposition models (Freeman–Durden, Cloude–Pottier, and Yamaguchi) for lunar crater-specific scattering analysis, enabling classification of regolith textures, and roughness parameters — aspects previously underexplored for lunar applications.

3. Development of an interdisciplinary framework integrating SAR-based physical surface analysis with geochemical nutrient mapping, thereby bridging the gap between remote sensing technology and lunar habitability studies.

4. First comparative assessment of lunar elemental concentrations (Mg, Fe, Ca, Na, Al, Si) with global agricultural nutrient standards, identifying potential zones for soil engineering and hydroponic cultivation in controlled lunar habitats.

5. Identification of critical elemental deficiencies (notably nitrogen, phosphorus, and potassium) in the lunar regolith that limit direct plant growth, thereby informing future ISRU strategies and extraterrestrial sustainability planning.

6. Enhanced understanding of radar scattering from lunar regolith and polar ice-like features, aiding future landing site selection, exploration planning, and terrain modeling in upcoming lunar missions (e.g., Chandrayaan-3 and Artemis).

By addressing both scientific and application-oriented dimensions, this research advances the state-of-the-art in lunar remote sensing and contributes to India's planetary exploration objectives. It lays a foundational methodology for future work in lunar resource utilization, in-situ agriculture feasibility, and advanced SAR modeling for extraterrestrial terrains.

6. Organization of Thesis

The present research work carried out in my research tenure has been combined in the form of a thesis entitled **"Study of Scattering Behaviour of Lunar Surfaces Using Chandrayaan-2 Polarimetric SAR".** This work has been broadly divided into seven chapters.

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1.3.5 The 21st-Century Resurgence: International and Cooperative Exploration
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1.11 Scope and Significance of the Research
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6.4.1.1 Freeman–Durden Decomposition: Odd-Bounce (Surface Scattering)

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6.4.2 Pauli Decomposition Analysis

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7.5.5 Analogue Studies on Earth

7.5.6 Contribution to Human Settlement and Agriculture

7. Conclusion

This study uses Chandrayaan-2's DFSAR polarimetric SAR data to examine how radar signals scatter off the Moon's surface. By analyzing different types of scattering—such as **single-bounce** (like from smooth surfaces), **double-bounce** (like between rocks and vertical structures), and **helix or multiple-bounce** (from complex or rough terrains)—we can understand the surface roughness, texture, and material variations of the lunar regolith in detail. Combined with elemental maps from the CLASS instrument, it provides an integrated analysis of the Moon's physical and geochemical features. The research supports future missions like Chandrayaan-3 and Artemis by identifying regions suitable for In-Situ Resource Utilization (ISRU). Ultimately, it offers a novel approach to evaluate the agricultural potential of lunar regolith, contributing to sustainable space habitation.

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9. List of Publications/Conferences Attended

1. 10 December 2023 to 13 December 2023 Actively Participated in Four days International Conference on Workshop “ 2023 IEEE India Geoscience & Remote Sensing Symposium (InGARSS)” organized by IIIT, Bengluru.
2. 23 March 2023 to 24 March 2023 Actively Participated & Organised in Two days International Conference on Workshop “ International Conference On Materials Science & Nanotechnology For Sustainable Applications” organized by UDICTE, MGM University AURANGABAD
3. 20 January 2024 Actively Participated in One days National Conference on “ Modern Trends In Physical Science Research (MTPSCR -2024)” organized by Bhalabhim Arts, Science & Commerse college Beed.
4. Presented and Publised paper titled “Basic Polarimetric Characteristics of Full-Polarization Chandrayaan-2 DFSAR Data Analyzed Using MIDAS” at the National Conference on Emerging Trends in Physics and Mathematics (ETPM-2024) organized by Anandrao Dhonde Alias Babaji Mahavidyalaya, Ashti, on 5th September 2024.
5. Successfully completed an online course on “AI/ML for Geodata Analysis”, conducted by IIRS–ISRO Dehradun from 19th August to 23rd August 2024. Achieved 100% attendance through the Nodal Centre at SOET, MGM University, Chhatrapati Sambhajinagar.
6. Completed a certified short-term course on “SAR Remote Sensing Technologies and its Applications” organized by IIRS–ISRO, Dehradun, from 7th to 25th October 2024, focusing on advanced radar remote sensing techniques for Earth and planetary studies.
7. Presented and Published paper titled “Comprehensive Analysis of Scattering Mechanisms in Lunar Crater Features Using Chandrayaan-2 DFSAR Data and Polarimetric Decomposition Techniques” at the International Conference on Climate Change (ICCC-2025) organized by SNDT Women’s University, Mumbai in collaboration with CUNY, USA, held from 16–18 January 2025.
8. Presented a research paper titled “Advanced Polarimetric Morphologies Using Chandrayaan-2 SAR Data” at the International Conference on Nano-Bio-Info and Cogno-Technology for Societal Benefit (ICNBICT-2025), held at MGM University, Chhatrapati Sambhajinagar on 24–25 March 2025. Secured First Prize in Oral Presentation.
9. Communicated a research paper titled “Using FAO Nutrient Standards and Chandrayaan-2 Elemental Maps to Assess the Agricultural Potential of Lunar Regolith” to the Jordan Journal of Physics (JJP) on 2nd July 2025, focusing on lunar soil nutrient mapping and agricultural feasibility.
10. Communicated a research paper titled “Assessing Lunar Regolith for Agriculture Using Chandrayaan-2 XRF and DFSAR” to the Journal of Theoretical and Applied Physics on 3rd July 2025, integrating radar and geochemical data for lunar agricultural assessment.

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